Simulation and Fuzzy Logic Analysis on an Off-road HEV

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Abstract—**Increasingly, the performance demands are being placed on vehicle control system. Fuzzy logic control has been proven to be an active and important approach to many mechanical and industrial systems, and has been widely accepted as an alternative approach to conventional control techniques. The hybrid electrical vehicle (HEV) has draw researchers' attention recently as well. This paper mainly discusses the control strategy of HEV based on fuzzy logic. By using this control strategy, the work space and work efficiency of engine are optimized, which play a vital role on improvement of the operation performance of HEV. Meanwhile, the strategy has been applied to optimize the power balance of battery, which includes the characteristics of battery in the controller. Besides, fuzzy control is used to implement parallel drive force distribution, which can easily achieve a variety of factors, especially for the compromise of battery SOC. Based on the Matlab/Simulink, the simulation results confirmed the excellent effectiveness of our control strategies, which optimized the fuel consumption of engine and the power balance of battery successfully.**

Keywords*— *Hybrid Electric Vehicle; Control Strategies; Fuzzy Logic; Off-road Vehicle; Simulation

I. INTRODUCTION

In recent years, there is huge attention for low greenhouse gas (GHG) emission and independence to the fossil fuel energy sources on the world. Recent surveys [1] show that 39.2% of total emissions in 2007 were caused by transportation. Vehicle manufacturers and global laboratories have focused on electric vehicles to reduce carbon emission and fossil fuel energy consumption. Many projects about electric vehicles are engaged to figure out solutions for future. A number of configurations of electric vehicles are designed to approach these objectives.

Electric vehicles (EV) include battery electric vehicles (BEV), hydrogen fuel cell electric vehicle (FCEV) and hybrid electric vehicle (HEV). BEV is generally suitable for compact electric vehicle at short range and low speed community transportation, which requires relatively small battery size. Although HEV can meet consumers' need for advanced performance, the major shortcoming is from its high cost. FCEV has been regarded as a main stream vehicles in future with long term potential, however the technology is still in early development stage at present, whose cost and refueling system are the major concerns [2]. Nowadays, the plug-in hybrid electric vehicles (PHEV) and hydrogen fuel cell plug-in hybrid vehicles (FCHEV) which are combinations of BEV, HEV and FCEV [3, 4] are being studied by technology researchers.

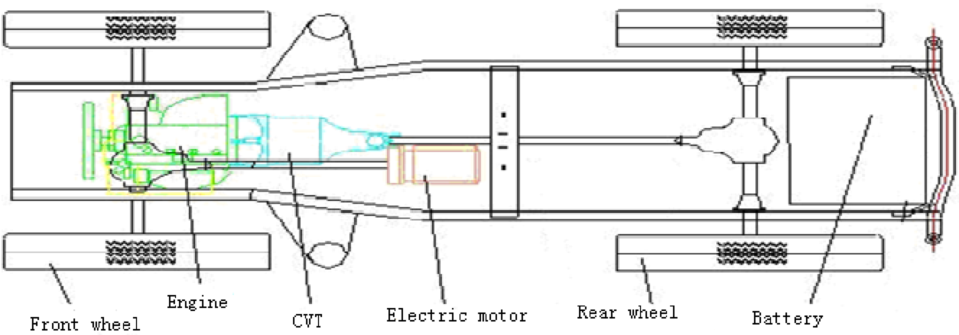


Fig.1 Configuration of CS7 4WD Hybrid Electric Off-road Vehicle System

In the literature, one can find a multitude of studies about HEV. As in [2, 6–9], studies have focused on the general hybrid configurations. The studies about power electronic components were presented in [4, 5, 10]. Apart from these research aspects of HEV, various energy management strategies of HEV were developed as in [6, 10–12]. As to the technique of powertrain control, including the control strategy and failure diagnosis, it has been regarded as the key technique of hybrid power. There are numbers of papers presented about the control strategy of hybrid power among the research area of hybrid power vehicle. In this domain, the management of energy and powertrain control system plays a vital role. At present, the strategies of hybrid power vehicle consist of logical threshold value control, intelligent control, global optimistic control and real-time optimistic control.

However, there remains be lack of published papers on 4WD Hybrid Electric Off-road Vehicle study. Fig. 1 is the configuration of CS7 4WD Hybrid Electric Off-road Vehicle System, which is Parallel Hybrid Electric Vehicle. The key technology of hybrid electric vehicle control is how to make the engine, electrical work in the high efficiency zone. Generally, when the battery is fully charged through the grid, the first choice is to drive in the pure electric mode. The engine will not begin to work until the battery SOC drops to a certain extent, meanwhile, we have to ensure the engine's efficiency and control the battery SOC value in a certain range. In order to deal with such a dilemma, in this paper, a new control strategy was developed to focus on the development of four-wheel hybrid drive mode.

II. FUZZY CONTROL STRATEGY FOR 4WD OFF-ROAD HEV

In this paper, there are three kinds of drive patterns: electrical model (front-wheel drive), engine drive model (rear-wheel drive) and hybrid drive model (four-wheel drive) have been researched. Normally, after charging the storage battery via electrical fence, the first choice of drive model is electrical model. With the decrease of SOC of battery, the engine drive model is launched to work gradually. In this way, four-wheel drive is the main drive model. Under this model, not only guarantee of high efficiency of engine but the control of SOC value is important. Therefore, to propose the control strategy focusing on four-wheel hybrid drive model, keeping the high efficiency of both engine and electrical motor is the key technique.

A. Fuzzy Control Strategy of Optimistic Curve

The main control principle of hybrid powertrain vehicle is the solution method focusing on the shortage of traditional vehicles, such as the high consumption of petrol, poor exhausting condition and low efficiency during the idle and low speed conditions. The engine universal performance characteristics map of traditional engine is shown in Fig. 2a. It is noticed from the map that the relative high consumption of oil at low engine speed condition. The highest efficiency of engine working conditions has been highlight by the pane in Fig. 2b. Under the same rotation speed of engine, the consumption of oil varies with the change of engine torque. Thus, it is possible to find out an optimistic working curve among the working domain, so that the engine would achieve the highest efficiency of fuel and excellent exhausting under the working condition. In this end, the main control strategy is to control the working condition of the engine, so that it can keep working in the optimistic working curve, then, meet with the demand the engine via adapt the auxiliary power.

The synthesis of power system is the task of control strategy for hybrid power vehicle. However, through the inspection of the economic fuel consumption and exhausting MAP figures it is noticed that the high efficiency area of fuel consumption does not coincide with the low exhausting area, as shown in Fig. 3. The bold line in the figure represents the largest torque area, while the corresponding optimistic exhausting area is within the ellipse area. It could be deduced for the Fig. 3 that only when the engine working within a limited small area, the optimistic condition of economic fuel consumption and the exhausting could be achieve simultaneously. That’s why the aim of control system for multiple hybrid power vehicle gains one of the optimistic economic fuel consumption and the exhausting only, or strike a balance value between these two.

To achieve the target, most of the control strategies at present start from the optimistic operation point of engine, and consider the balance of battery SOC at the same time, so that the optimistic control curve would be gain. When the torque or speed of the hybrid power vehicle achieves a particular switching value, the drive model would transfer from electrical model to engine model. Under such a hybrid model, the engine is working on the optimistic operation curve, for the gap between the output torque and drive torque is compensated by the electrical pattern. Only when the battery SOC is not enough, the operation point of engine would apart from the optimistic curve [13].

In this paper, fuzzy control is used to implement parallel drive force distribution. Since fuzzy control have advantages of strong anti-interference ability and good robustness, it is very suitable to express the control rules in HEV which are very difficult to be precisely expressed by other control strategies. Besides, the fuzzy control can also easily achieve a variety of factors, especially for the compromise of battery SOC.

For the parallel system，the foremost objective of the control system is to keep the engine fitting to the optimal function curve properly during work. Only when the battery SOC is too low or too high and the torque of the motor cannot meet the vehicle torque will the engine's operating point deviate from the optimal curve. Meantime it is also very important to maintain the battery SOC to change in its reasonable range.

According to the objectives mentioned above, the input variables of the fuzzy controller are the difference △Tec between the torque demanded for the vehicle and the current corresponding torque of the engine optimizal curve, battery state of charge value SOC, and output of the fuzzy controller is identified as the engine torque command Tec. The controller structure is shown in Fig. 4.

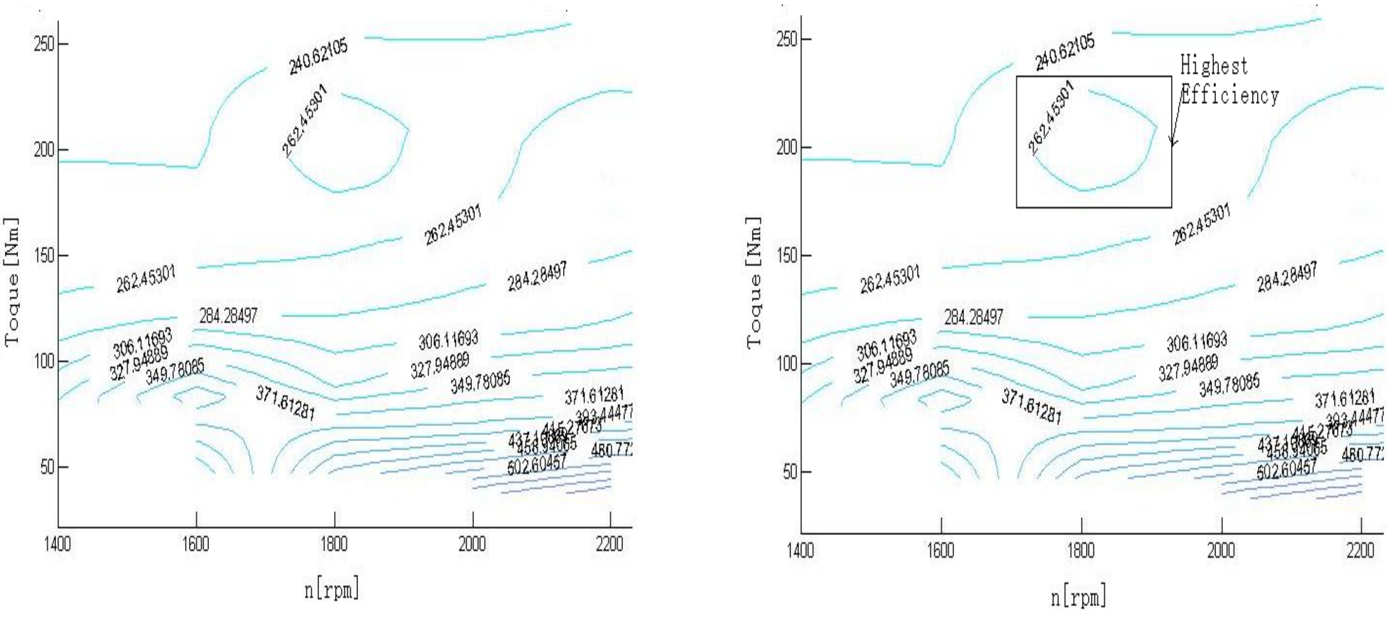
In determining the input and output volume on the field, the torque of the two input parameters are taken normalized respectively, i.e., there are divided by the maximum engine torque, and then be processed to calculate the value obtained. When the field changes into [-1.2,1.5], the output Tec field is obtained as [0,1] using the same method. The domain of battery SOC value is [0,1]. The input and output variables with fuzzy sets are as follows:

Fuzzy set of △Tec:{NB，NM，NS，ZE，PS，PM，PB}

Fuzzy Set of SOC：{low，optimal，high}

Fuzzy Set of Tec：{PS，PM，PB，PBB}

In the three sets above, it has been assumed that NB means the negative big; NM means the negative mid; NS means the negative small; ZE means zero; PS means positive small, PM means the positive mid; PB means positive big; PBB means positive greater; optimal means normal. The membership functions are chosen by simulation results and experience, and the fuzzy inference system used Mamdani system. By using the MATLAB toolbox, the designed fuzzy control input, output membership functions are shown in Fig. 5.



(a) engine universal performance characteristics map

(b) The highest efficiency of engine working conditions

Fig. 2 Efficiency of Engine

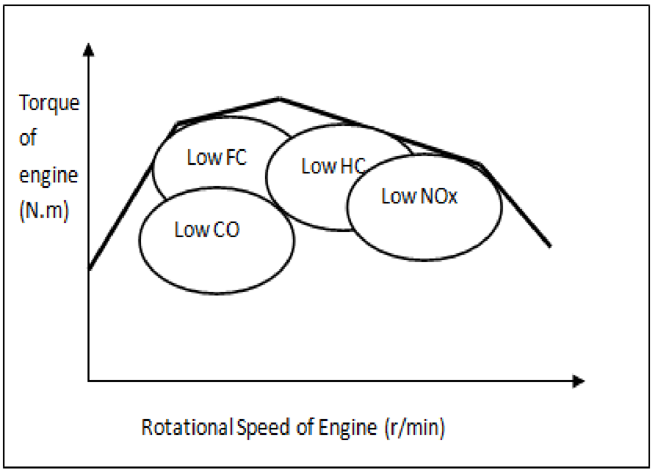


Fig. 3 Distribution of economic fuel consumption and exhausting of engine

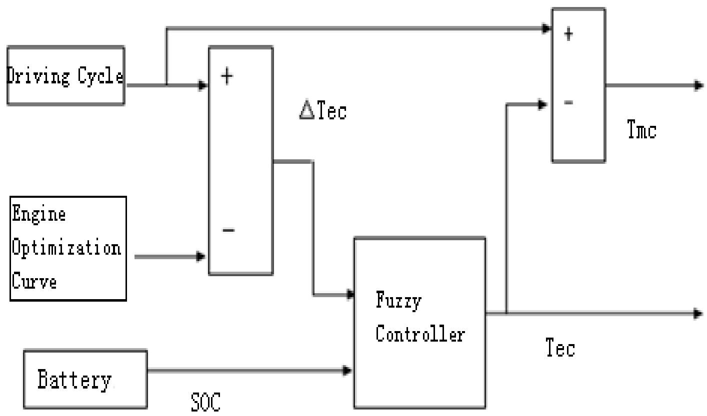


Fig. 4 Structure of Fuzzy Logic Controller

B. Control Strategy of Battery SOC Balance

How to control the battery SOC balance in the loop condition before and after the control strategy is a much more important part, as it plays key role in the vehicle economy. As control strategy is usually not able to maintain the power balance by itself, even the more successful control strategies can only keep the batter SOC changing in a certain range, thus it is necessary to develop a special battery power balance control strategy to help the most fuzzy control curve to achieve better control performance.

During the driving process of HEV, the battery is supplemented in two ways, through the engine to charge and braking energy recovery. If we can take advantage of the regenerative braking mode, the engine charge will be less dependent or even unnecessary. Apparently, if that, the vehicle fuel economy will naturally increase. In general, people are concerned about change of the battery in a whole loop whole, not every moment. Therefore, if considering the global power balance during driving cycle, we canprevent the engine and electric motor charge occuring constantly in turns back and forth, and reduce the efficiency losses and improve vehicle fuel economy.

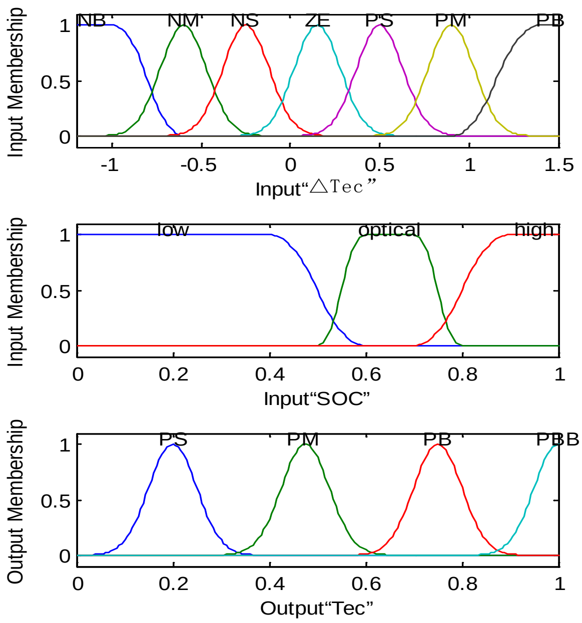


Fig.5 Input and Output of Fuzzy Controller

In the absence of power balancing strategies, through the analysis and comparison of the simulation results, it can be found that in most of the driving cycle, the battery SOC value is at downward state in the end as shown in Fig. 8.

The main reason for this phenomenon is that the energy recovered from braking is insufficient to meet the needs of the motor without using the power balancing strategies. Our study will address this situation of insufficient energy recovery capacity to develop appropriate power balance strategy. Adjusting the output of fuzzy control unit on the engine torque required method of membership function can achieve energy balance. It means that the parameters of fuzzy sets, PS, PM, PB and PBB appropriate pan right respectively, and increase the requirements of engine torque. The increased part of torque can be used to generate electricity to supplement the battery.

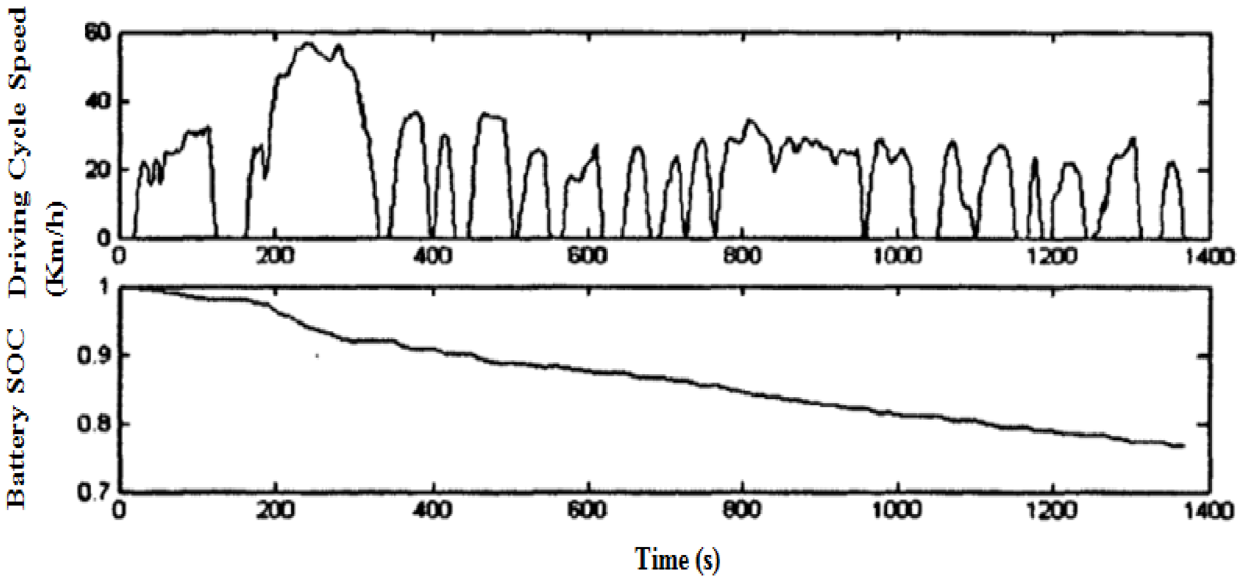


Fig.8 UDDC Driving Cycle

The fuzzy control unit is based on Mamdani method. It has two input parameters and one output parameter shown in Figure 9. Two input parameters are the SOC value of the level and rate of change in the end of the driving cycle. The level of SOC values is reflected by the difference between target control value of SOC and the SOC vales at the end of driving cycle. If this parameter is negative, it is indicating that the current SOC value is a little too high compared with the target SOC value. If this parameter is positive, it is indicating that the current SOC values is a little too low compared with the target control value, and if this parameter is zero, it is indicating that the current value reaches the target SOC control values. The change rate of SOC is reflected depending on the difference between the values at the end and beginning of driving cycle. If this parameter is positive, it means that the battery vale is increased slightly at the end of the driving cycle, otherwise, it decreased.

Parameters of membership function are shown in Fig. 10. In the figure, SOC means the battery level at the end of the loop drive; SOC-rate means the change rate of SOC; Tec ' means the required adjustment value to the engine torque. The SOC sets include high, normal and low, which represent the current SOC values is higher, or lower, or normal compared the target control value respectively. And, N, Z and P mean negative, zero, and positive in the SOC-rate of the fuzzy sets, respectively.

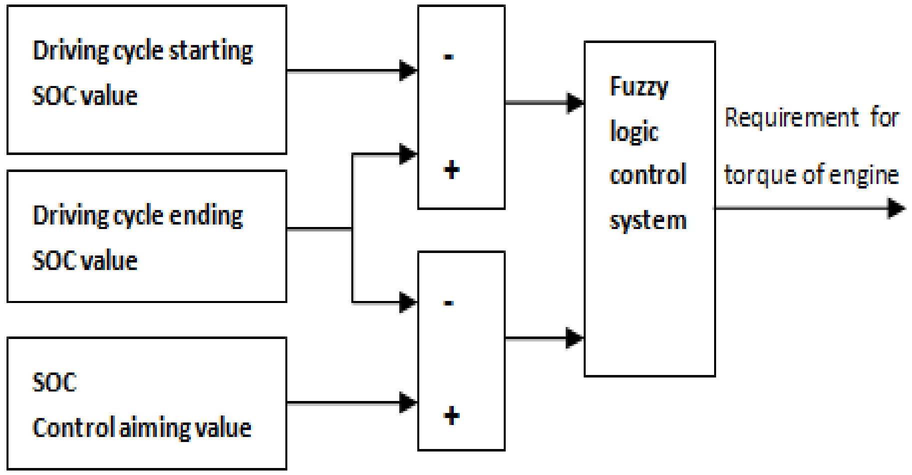


Fig.9 Structure of power balance controller

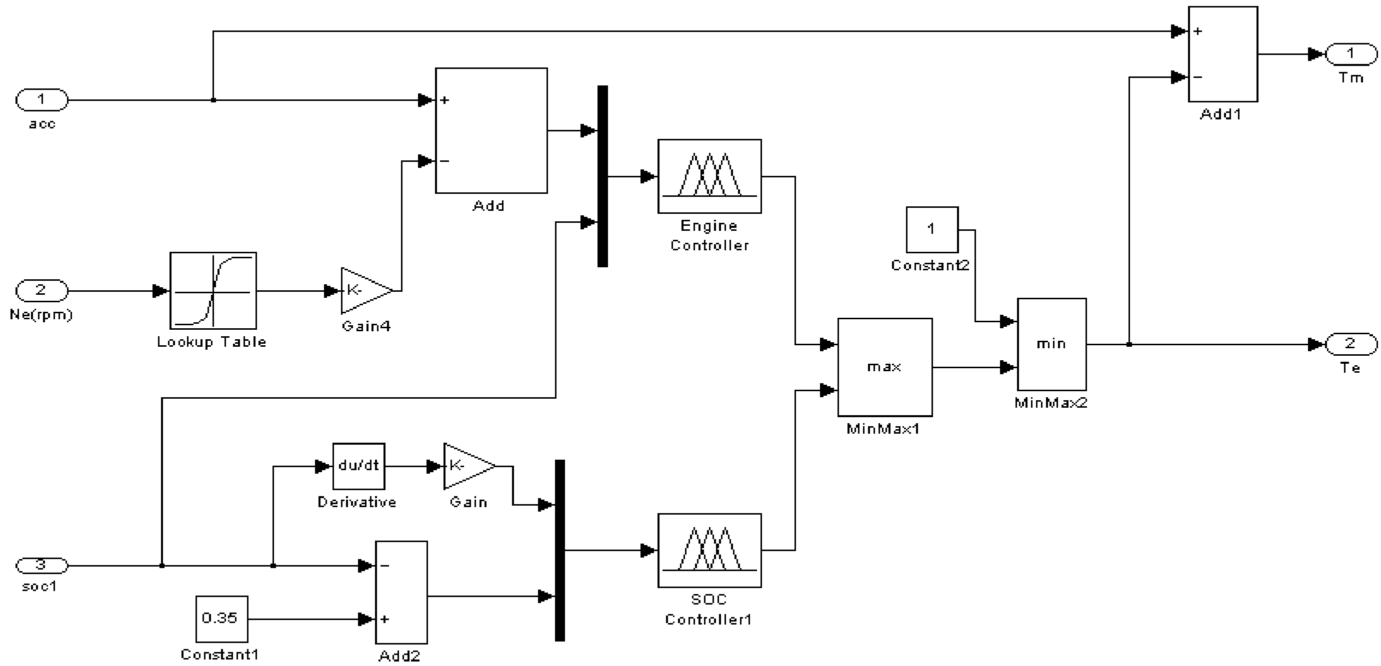


Fig.12 Fuzzy Control Simulation Module on SOC balance

The following is about the basic control rules. (1) When the battery SOC value is low (low), if the SOC change rate is negative, which means SOC values will continue to reduce, there should be a substantial increase in engine output torque to make the SOC value of pick-up; if SOC rate of change is Zero, indicating that SOC values will not continue to decrease, the output torque can pass over the best torque, and then increases somewhat; if the SOC change rate is positive, indicating that SOC value is picking up, the output torque of the engine can be reduced slightly. (2) When the battery SOC value is in the normal balance range (normal), if the SOC change rate is negative, which means that SOC will decrease, meaning that there should be a slight rise for the output torque of the engine to correct the SOC downward trend; If the SOC change rate is zero, there should be a slight reduction in engine torque output; if the SOC change rate is positive, indicating that SOC values will rise, the engine torque output should be a little larger to reduce SOC values the upward trend. (3) When the battery SOC value is high (high), if the SOC change rate is negative, indicating that SOC value is restored to normal levels, which means that the engine torque output can be reduced slightly; when the SOC change rate is zero, it is the same as high; if changes in SOC rate is positive, indicating that SOC values will continue to rise, which could significantly reduce engine torque to reverse the rising trend of SOC values. The control rules as shown in Table I, and the control rule surface is shown in Fig. 11.

1) Input Parameter

The parameters for simulation are listed in Table II below.

2) Simulation Cycle

There are several standards, regulations and laws regular the drive conditions of vehicle around the world. Usually, to test the exhausting of vehicle on the drive there are three popular rules: United States' Drive Condition (USDC), European Drive Condition (EDC) and Japanese Drive Condition (JDC). At present, the most popular standard is the New European Drive Condition (NEDC), which is consist of four cities' cycles of steady motions and one 400 second suburb highway working condition. Thus, the NEDC is adopted in the simulation analysis in this research.

IV. RESULTS AND ANALYSIS

Based on NEDC drive cycle, the model simulation results are obtained, including driving cycle velocity, electric-motor torque, engine output, value of battery soc, showed in fig. 14. The results show that (1) during the rising phase of driving cycle velocity, in order to meet the power requirements for vehicle, the engine and electric motor provide output torque simultaneous, and the value of SOC is decreasing; (2) during the downward phase of velocity, the engine stops working, while the output toque of motor is negative which means that it is in the power generation state, and the value of SOC increased slightly. From the results we can know that the value of SOC is generally in declining, but it can be maintained in the safe discharge state. According to the simulation results, when the initial value of SOC is 0.5, the hundred kilometers oil consumption is 7.61L, which means that the fuel efficiency is good.

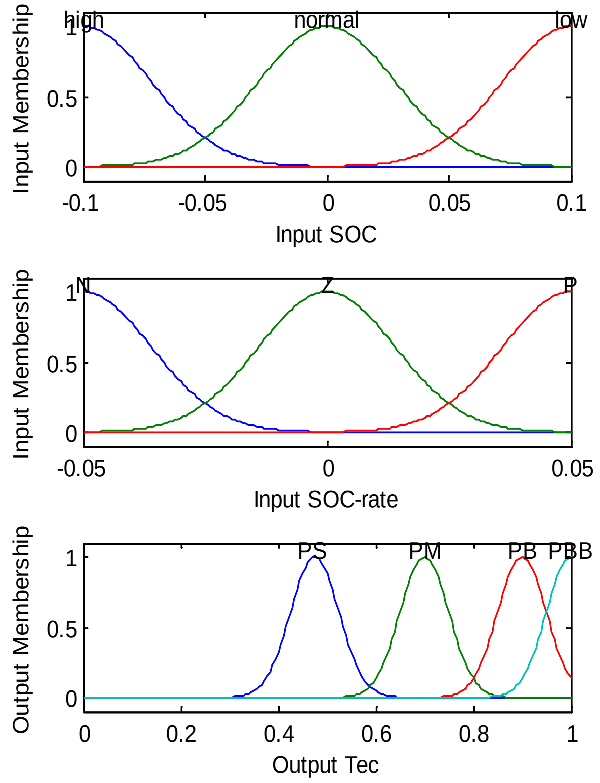


Fig.10 Input and Output of Battery Balance Fuzzy Controller

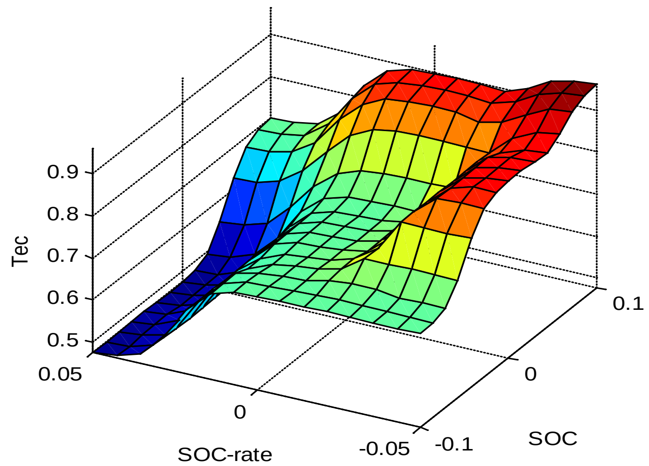


Fig.11 Surface of Fuzzy Control Rules on power balance

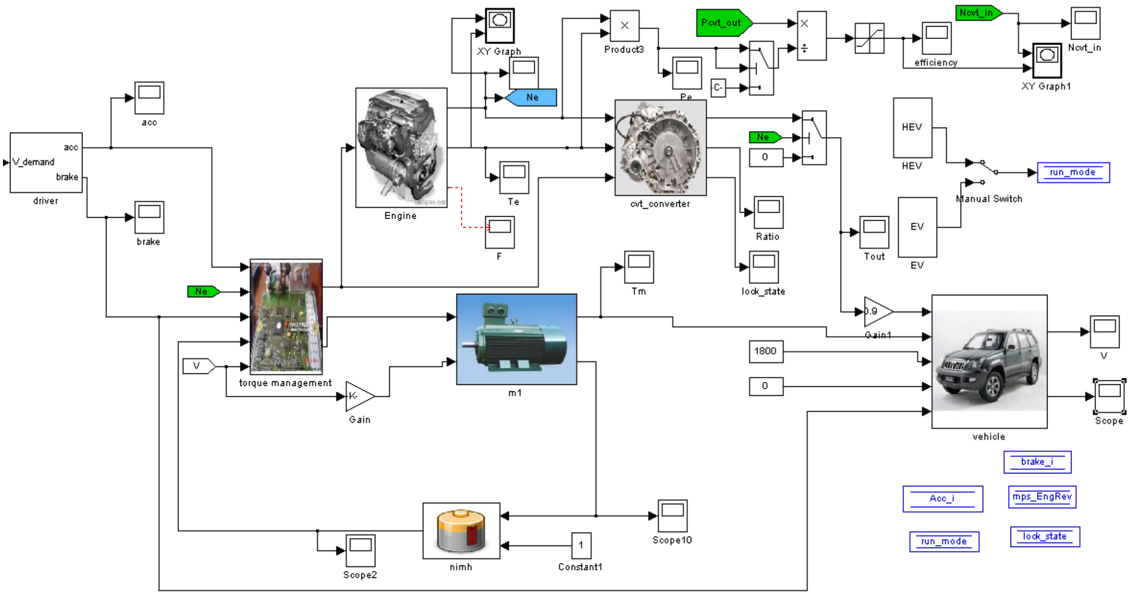


Fig. 13 Matlab/Simulink HEV Top Model System

TABLE 2 SIMULATION PARAMETERS OF HYBRID POWER VEHICLE

NO.	Term	Value	Unit
1	Total Mass	1800	kg
2	Total Length	4210	mm
3	Total Wealth	1730	mm
4	Total High	1700	mm
5	Wheelbase	2550	mm
6	Radius of Gear	0.343	mm
7	Coefficient of Rolling Resistance	0.018	-
8	Front Face Area	2.66	m2
9	Coefficient of Air Resistance	0.44	-
10	Front Gauge	1443	mm
11	Rear Track	1453	mm
12	Front Overhang	760	mm
13	Rear Overhang	900	mm
14	Front-Wheel Drive Maximum Torque	170	Nm
15	Front-Wheel Drive Maximum Speed	7200	r/min
16	Front-Wheel Drive Maximum Capacity	37	kw
17	Maximum Power of Engine	69	kw
18	Maximum Torque of Engine	135	Nm
19	Engine Capacity	1.5	L
20	Cell Voltage	288	V
21	Number of Cell	90	-
22	Marker Capacity of Cell	30	Ah
23	Final Drive Ratio	4.636	-

TABLE 1 CONTROL RULES

SOC-rate / SOC	N	Z	P
high	PM	PM	PS
normal	PB	PM	PS
low	PBB	PB	PM

V. CONCLUSIONS

The major contribution of this work is the development of a control strategy of HEV based on fuzzy logic. The strategy has been proved to be effective on optimizing the work space and work efficiency of engine which is of great importance in HEV control system. Further study has applied the strategy of the power balance of battery has optimized by fuzzy logic and the characteristics of battery is included in the controller, and the corresponding model founded by Matlab/Simulink had been inserted into the system. The results of simulation show

that the mentioned strategy is effective. It cuts down fuel consumption and keeps battery power balanced.

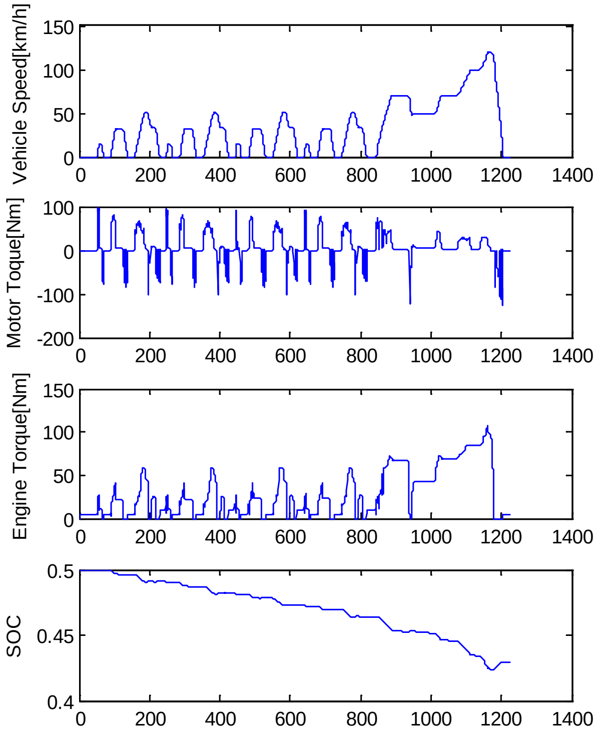


Fig.14. NEDC Simulation Results

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